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## The stealthy Higgs model at future Linear Colliders<sup>a</sup>

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We investigate the influence of scalar gauge singlets on Higgs signals at a linear collider. These lead to a large invisible decay width of the Higgs. We find that for high luminosities ( $500 - 1000 fb^{-1}$ ) one can essentially cover the allowed parameter range of the model.

### 1 Introduction

Understanding of the electroweak symmetry breaking mechanism is one of the main tasks in particle physics. The establishment of the structure of the Higgs sector would be a break-through in our knowledge about matter. So it is important to think about alternatives to the Standard Model Higgs sector especially if they lead to a dilution of the signal. The simplest possible extension is the addition of scalar fields which are singlets under the gauge group of the Standard Model. Radiative corrections to weak processes are not sensitive to the presence of singlets in the theory, because no Feynman graphs containing singlets appear at the one-loop level. Since effects at the two-loop level are below the experimental precision, the presence of a singlet sector is not ruled out by any of the LEP1 precision data. The only connection to such a hidden sector is a possible Higgs singlet coupling, leading to a nonstandard invisible Higgs decay. Whereas the invisible decay of the Higgs boson with a width comparable to the Standard Model leads to relatively sharp missing energy signals, e.g. well known from discussions on Majoron models<sup>2</sup>, a strongly coupled hidden sector could lead to fast Higgs decay and thereby to wide resonances. This would disturb the signal to background ratio if necessary cuts are imposed.

To check the influence of a hidden sector we will study the coupling of a Higgs boson to an  $O(N)$  symmetric set of scalars, which is one of the simplest possibilities, introducing only a few extra parameters in the theory. The effect of the extra scalars is practically the presence of a possibly large invisible decay width of the

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Higgs particle. When the coupling is large enough the Higgs resonance can become wide even for a light Higgs boson. It was shown earlier that there is a range of parameters, where such a Higgs boson can be seen neither at LEP nor at the LHC<sup>1,6,3</sup>.

## 2 The model

The scalar sector of the model consists of the usual Higgs sector coupled to a real  $N$ -component vector  $\vec{\varphi}$  of scalar fields, denoted by Phions in the following. The lagrangian density is given by,

$$\begin{aligned}\mathcal{L} = & -\partial_\mu\phi^+\partial^\mu\phi - \lambda(\phi^+\phi - v^2/2)^2 - 1/2\partial_\mu\vec{\varphi}\partial^\mu\vec{\varphi} - 1/2m^2\vec{\varphi}^2 \\ & -\kappa/(8N)(\vec{\varphi}^2)^2 - \omega/(2\sqrt{N})\vec{\varphi}^2\phi^+\phi\end{aligned}$$

where  $\phi$  is the standard Higgs doublet. Couplings to fermions and vector bosons are the same as in the Standard Model. The ordinary Higgs field acquires the vacuum expectation value  $v/\sqrt{2}$ . For positive  $\omega$  the  $\vec{\varphi}$ -field acquires no vacuum expectation value. After spontaneous symmetry breaking one is left with the ordinary Higgs boson, coupled to the Phions into which it decays. Also the Phions receive an induced mass from the spontaneous symmetry breaking which is suppressed by a factor  $1/\sqrt{N}$ . If the factor  $N$  is taken to be large, the model can be analysed with  $1/N$ -expansion techniques. By taking this limit the Phion mass is suppressed, whereas the decay width of the Higgs boson is not. Because the Higgs width is now depending on the Higgs Phion coupling its value is arbitrary. Therefore the main effect of the presence of the Phions is to give a possibly large invisible decay rate to the Higgs boson. The invisible decay width is given by

$$\Gamma_H = \frac{\omega^2 v^2}{32\pi M_H} = \frac{\omega^2 (\sin\theta_W \cos\theta_W M_Z)^2}{32\pi^2 \alpha_{em} M_H} \quad . \quad (1)$$

The Higgs width is compared with the width in the Standard Model for various choices of the coupling  $\omega$  in Fig. 1. The model is different from Majoron models<sup>2</sup>, since the width is not necessarily small. The model is similar to the technicolor-like model of Ref.<sup>5</sup>.

Consistency of the model requires two conditions. One condition is the absence of a Landau pole below a certain scale  $\Lambda$ . The other follows from the stability of the vacuum up to a certain scale. An example of such limits is given in Fig. 2, where  $\kappa = 0$  was taken at the scale  $2m_Z$ , which allows for the widest parameter range. The regions of validity up to a given scale  $\Lambda$  is sandwiched between the upper-right and the lower-left contour lines in the figure. The first stem from the Landau pole, the second from instability of the vacuum at that scale.

To search for the Higgs boson there are basically two channels, one is the standard decay, which is reduced in branching ratio due to the decay into Phions. The other is the invisible decay, which rapidly becomes dominant, eventually making the Higgs resonance wide (see Fig. 1). In order to give the bounds we neglect the coupling  $\kappa$  as this is a small effect. We also neglect the Phion mass. (For other

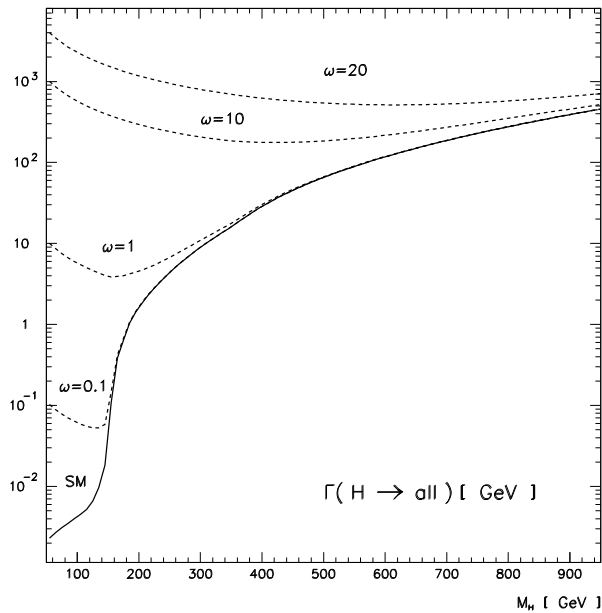


Figure 1: *Higgs width in comparison with the Standard Model.*

values of the Phion mass the bounds can be found by rescaling the decay widths with the appropriate phase space factor.)

### 3 LC bounds

At a linear collider (LC) the upper limits on the couplings in the present model come essentially from the invisible decay, as the branching ratio into visible particles drops with increasing  $\varphi$ -Higgs coupling, whereas for the Higgs mass limits one has to consider visible decays, too. The  $WW$ -fusion process can not be used to look for invisible Higgs decay. One is therefore left with the Higgsstrahlung und  $ZZ$ -fusion reaction. For energies up to 500 GeV the Higgsstrahlungs cross section is dominant and still comparable if one multiplies with the branching ratio  $B(Z \rightarrow e^+e^-, \mu^+\mu^-)$ . The Higgsstrahlungs reaction is preferred, because one can tag the on-shell Z boson. Thus we only have considered reactions containing an on shell Z boson with its decay into  $e^+e^-$  or  $\mu^+\mu^-$ . The signal cross section is the well known Higgsstrahlungs cross section modified by the non standard Higgs width due to Phion decay. With the invariant mass of the invisible Phion system,  $s_I$ , it reads:

$$\sigma_{(e^+e^- \rightarrow Z+H)} = \int ds_I \sigma_{(e^+e^- \rightarrow ZH)}(s_I) \frac{\sqrt{s_I} \Gamma(H \rightarrow H)}{\pi((M_H^2 - s_I)^2 + s_I \Gamma(H \rightarrow \text{All})^2)} \quad (2)$$

To reduce the  $Z\nu\nu$  background<sup>7</sup>, we used the fact that the angular distribution

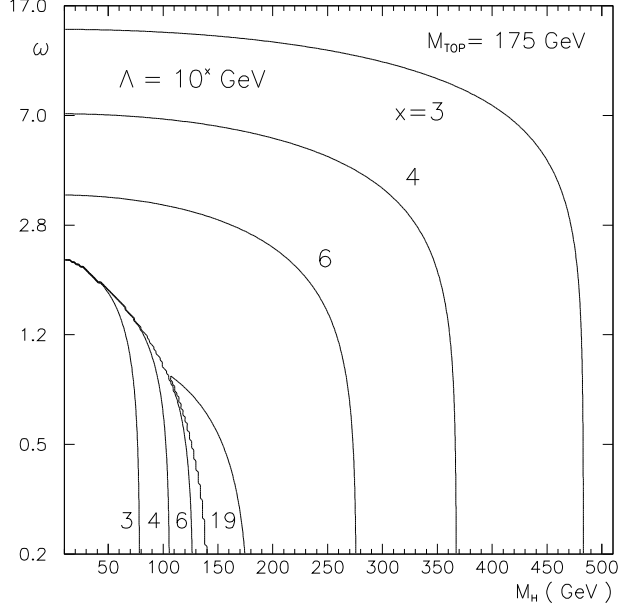


Figure 2: *Theoretical limits on the parameters of the model in the  $\omega$  vs.  $M_H$  plane. The contour lines correspond to the cutoff scales  $\Lambda = 10^{19}, 10^6, 10^4$  and  $10^3$  GeV.*

of the Z-boson for the signal peaks for small values of  $|\cos\theta_Z|$  in contrast to the background. Thus we imposed the cut  $|\cos\theta_Z| < 0.7$ . Because we assume the reconstruction of the on-shell Z-boson we use the kinematical relation  $E_Z = (\sqrt{s} - M_Z^2 + s_I)/(2\sqrt{s})$  between the Z energy and the invariant mass of the invisible system to define a second cut. Because the differential cross section  $d\sigma/ds_I$  peaks at  $M_H^2$ , we impose the following condition on the Z energy:

$$\frac{\sqrt{s} - M_Z^2 + (M_H - \Delta_H)^2}{2\sqrt{s}} < E_Z < \frac{\sqrt{s} - M_Z^2 + (M_H - \Delta_H)^2}{2\sqrt{s}} \quad (3)$$

For the choice of  $\Delta_H$  a comment is in order. As long as the Higgs width is small one is allowed to use small  $\Delta_H$ , which reduces the background considerably keeping most of the signal events. But in the case of large  $\varphi$ -Higgs coupling,  $\omega$ , one loses valuable events. To compromise between both effects we took  $\Delta_H = 30(100)$  GeV for colliders with center of mass energy of 500(1400) GeV, respectively.

For the exclusion limits we assumed an integrated luminosity of 500 (1000)  $fb^{-1}$  for the two center of mass energies. To define the 95% confidence level we used Poisson statistics as in Ref. <sup>6</sup>. The result is given in Fig. 3.

We conclude from the above that a LC with the proposed high luminosities can essentially cover the parameter range up to the theoretically allowed limit with a completely clean signal, consisting of leptons plus missing energy. Such a LC appears to be the unique machine to be sensitive to this class of models.

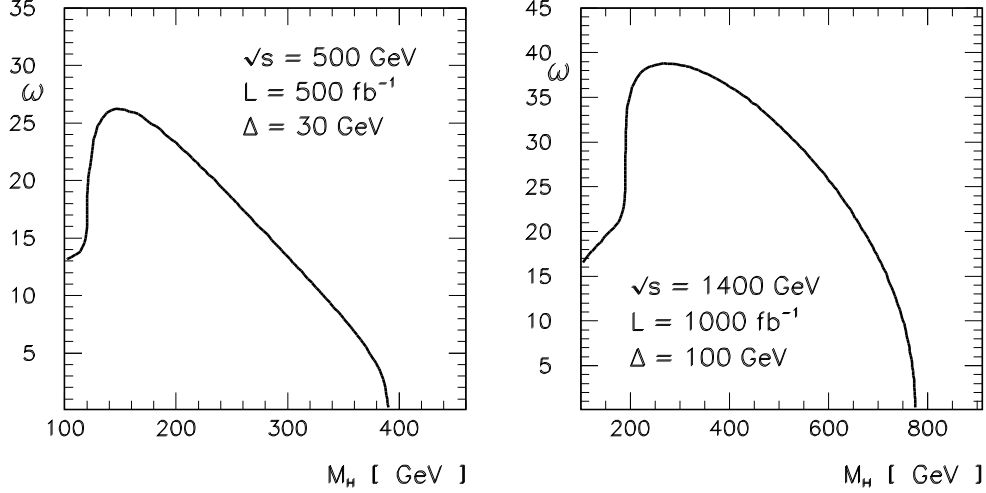


Figure 3: *Exclusion limits at a LC at an energy of 500 (1400) GeV and luminosity 500 (1000)  $fb^{-1}$ , respectively.*

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